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5. INTRODUCTION

The goal of any breast imaging modality is to improve the early detection of tumors and to improve the differentiation between benign and malignant lesions. While x-ray mammography is efficacious in diagnosing a high percentage of breast masses, it also produces a high rate of false positives [1]. The percentage of breast biopsies that are actually malignant vary between 10 % and 35 %. Thus, a technique which reliably differentiates between malignant and benign masses would improve the diagnosis of breast cancer and should, therefore, reduce the number of negative biopsies as well as the trauma of the patients. This project attempts to establish such a technique through the novel and innovative combination of three-dimensional (3D) ultrasound imaging with a contrast agent.

Ultrasound imaging is currently an auxiliary modality in breast imaging. It is mainly used to differentiate between cystic and solid lesions [2]. Investigations into the possibility of breast cancer diagnosis based on Doppler ultrasound flow detection have produced mixed results, due to overlap between flow measurements in benign and malignant tumors [3-4]. One problem may be the lack of sensitivity in flow detection in small tumor vessels using ultrasound. This hypothesis is supported by reports in the pathology literature describing angiogenic vascular morphology as an independent predictor of metastatic disease [5].

Ultrasound contrast agents produce increases of 15 to 25 dB in the echo intensities of blood flow signals; especially when combined with a new display technique called color amplitude imaging (CAI) [6-7]. Thus, an interesting research study can be devised, which compare the ability of two-dimensional (2D) color Doppler ultrasound with and without contrast to differentiate between benign and malignant masses relative to x-ray mammography. This is in essence the purpose of a 5 year National Institutes of Health (NIH) funded project recently awarded to Thomas Jefferson University. The current project (DAMD17-97-1-7116) is an expansion to the NIH project which adds 3D flow imaging with and without contrast, since 3D imaging should be better suited than 2D ultrasound to demonstrate the tortuous angiogenic vasculature associated with breast cancer.

Not only is the potential of the novel combination of 3D imaging and contrast in itself innovative, but because of the NIH funded study it will be possible to compare a number of new and unique approaches to breast cancer diagnosis i.e., 2D and 3D CAI with and without contrast as well as harmonic imaging directly to x-ray mammography. Furthermore, this project is extremely cost-effective because the NIH grant covers a majority of the personnel costs as well as all major equipment purchases. The amalgamation of the NIH project with the current proposal also allows for basic research into the correlation between Doppler flow signals and pathologically detected lesion vascularity. This will enable a deeper understanding of the relationship between tumor neovascularity and ultrasound flow measurements; again at very little cost to this proposal.

Consequently, this project is an add-on study to the already funded NIH project aimed at increasing the sensitivity and specificity of breast ultrasound by combining injection of an ultrasound contrast agent with 3D reconstruction of color amplitude images. The fundamental

hypothesis is that the neovasculature of malignant lesions can be visualized with this novel combination, thus, improving the diagnosis of breast cancer.

6. BODY

The central hypothesis of this project is that the differentiation between benign and malignant breast lesions can be improved by visualization of tumor neovascularity using 3D ultrasound imaging in conjunction with an ultrasound contrast agent. To investigate this hypothesis 150 women with breast lesions will be recruited over three years and imaged using contrast enhanced 3D CAI. The specific tasks of the project (as presented in the original Statement of Work) can be found in Appendix I.

First an outline of the methods applied will be given followed by a presentation of the results to date. Finally, the conclusions and future directions of the research will be discussed.

6.1 Methods

The 3D CAI reconstructions in this project are performed with a state-of-the-art ultrasound scanner connected to an LIS 6000A 3D Image Acquisition and Reconstruction system (Life Imaging Systems Inc, London, Canada). To date all 3D CAI acquisitions have been performed with an HDI 3000 scanner (Advanced Technology Laboratories, Bothell, WA). The 3D CAI data sets are reconstructed, with no loss of registration accuracy, to provide both multi-perspective Maximum-Intensity-Projection visualization and 2D planar views.

The patients used in this project will be women of a wide variety of ages having a breast mass or abnormality resulting in a breast excisional biopsy. Breast cancer in males accounts for only about 1 % of cases in our hospital and thus, were not be included in the patient population. All patients will be referred after X-ray mammography identifies a mass or suspicious area. The target enrollment is approximately 50 patients per year, which represents half of the patients being recruited for the NIH-supported study.

Following a baseline ultrasound gray scale scan, which identifies the mass seen by x-ray mammography, images for 3D CAI of the lesion are acquired. Next, an ultrasound contrast agent is administered intravenously via a peripheral vein, preferably the antecubital vein. An initial videotaped sweep of the mass will be made with the gain and CAI settings unaltered from the pre contrast settings. This will allow for side by side comparison of pre and post contrast CAI studies. Following this, the CAI settings will be optimized for the stronger contrast enhanced Doppler signals. As the SNR improves it should be possible to achieve higher frame rates and/or line density, improving spatial resolution of the color. Videotaped sweeps of the abnormality will be made every 1 to 2 minutes through the period of enhancement (up to 6 minutes). A second injection is made to acquire 3D CAI data with the gain and other settings unaltered from the pre contrast protocol. This will allow for side by side comparison of pre and post contrast 3D CAI studies. Next the CAI settings will be optimized for the stronger contrast enhanced signal, and 3D data will be acquired again.

The ultrasound findings will be correlated to the pathology sections and the radiologist and pathologist will attempt to correlate the findings by each method. If the ultrasound and pathology sections do not match it is possible in the 3D case to resection the acquired volume until a match is found. After removal of the mass, the specimens will be sectioned in the same plane as the ultrasound images and stained with an endothelial cell marker, CD31, which targets the microvessel walls staining them brown to dark brown in color. Finally, the sections will be mounted onto 2"x 3" glass slides. The vascular morphology of the tissue, specifically, the number and area occupied by tumor vessels, will be determined by a semi-automated histomorphometry system based on SMZ-10A microscope (Nikon, Melville, NJ) and ImagePro Plus software (Media Cybernetics, Silver Spring, MD). Using the software, microscope, and a Sony CCD camera, the entire specimen area is captured and digitized under 100x magnification. The frame size captured is equal to 640 pixels by 480 pixels or 1.27 mm². The number of color pixels on the color flow images relative to the pixel size of the mass can be used as a first order measure of mass vascularity [8]. Frozen ultrasound images will be captured before and after contrast injection and digitized using the image analysis software.

Both the slide and video image analyses are patterned after chromaticity analysis methods used by Barbareschi et al. and Bell et al., respectively [9-10]. The aim of the slide image analysis is to develop a method in which only microvessels with lumen would be recognized by the software and, hence, counted and measured. Only vessels with lumen will be chosen for three reasons: 1) the diameter of the vessels can be assessed directly, 2) other structures sporadically stained will not give false positives, and 3) a more repeatable and automated method can be performed. For each captured RGB color image of tumor area the slide image processing consists of extracting vessel (saturation image) and tissue (blue image) enhanced images and performing mathematical morphometry to obtain an image on which automated count and measurements of microvessels was performed. For each slide the total microvessel area (MVA) and count (MVC) will be determined and divided into five categories: vessel diameters between a) 10-19 μm , b) 20-29 μm , c) 30-39 μm , d) 40-49 μm , and e) 50 μm and above. The ultrasonic image processing consists of extracting red, green, and blue images and performing mathematical morphometry to obtain an image only with color pixels. From the video analysis, the percent of color pixels within the mass will be calculated for each level before and after contrast administration.

To determine if a linear relationship existed between pathologic and ultrasonic vascularity measurements, an equal number of data points must be assessed from both methods. Ten ultrasonic data points per patient (5 pre and 5 post contrast) will consistently be obtained because a hand held transducer is used and regardless of the size of the mass, scans at five levels of each mass can always be taken (albeit, sometimes with overlap between the levels). However, due to the size of some masses, five pathologic sections of a mass will sometimes not be possible. Therefore, to be able to compare the data sets two solutions were developed, which ensures equal number of points in both data sets. One solution requires ultrasonic data to be averaged and replaced until for each patient the number of scans equals the number of pathology slides (i.e., data reduction). The other solution requires pathologic data to be averaged and added to the number of slides for each patient until five data points were reached (i.e., data expansion). Statistical analysis is performed to determine if ultrasonic flow data (pre or post contrast)

correlated with pathologic data in breast tumors. The linear relationship between ultrasonic and pathologic data will be assessed using single and multiple variable linear regression techniques.

6.2 Results and Discussion

From September of 1999 and until November 1999, 8 additional patients with 3 cancers and 5 benign lesions have signed informed consent and been enrolled in the Optison arm of the study (Table 1). The patients had a mean age of 57 years (range 46 to 70 years). Currently, there are 21 patients in the Optison arm of the study. Since then no patients have been recruited. This delay occurred, because the research coordinator assigned to this project was promoted to grants administrator for the entire department in March of this year. This followed a prolonged period as temporary administrator (since November), due to the former grants administrator's terminal illness. Moreover, it has taken the University over 5 months to open up the research coordinator position. Hence, the project has effectively been without a coordinator for over 10 months, during which time no patients have been recruited. A new candidate for research coordinator has been hired and will start on October 31st, 2000. Consequently, a one year no-cost extension with a carryover of the unspent balance was requested and granted by the U.S. Army Medical Research And Material Command in August of 2000. The one year no-cost extension will be utilized to complete the project, including data collection and analyses. In summary, task 1 has been completed and tasks 2 and 3 are ongoing, but due to the unforeseen circumstances only limited progress has been made this grant year.

A subset of 14 patients with 39 pathology slides (for a total of 6610 frames) were examined with the histomorphometry system. A total of 140 digitized ultrasound scans (5 pre and 5 post contrast for each patient) were included in this part of the study. There was a significant increase in the number of ultrasound color pixels pre to post contrast injection ($p < 0.003$). No statistical difference in ultrasonic color pixels was found between the benign and malignant masses. Table 2 gives the r^2 values for the linear regression for the reduced and expanded data sets. The multiple linear regression technique for the entire data set (i.e., benign and malignant lesions evaluated jointly) found significant correlations for ultrasonic color pixels post injection with the percent of area in the five vessel ranges (expanded MVA; $p = 0.006$) and with the percent of vessels in the five vessel ranges (reduced iMVD; $p = 0.04$). No correlations were found between pre contrast ultrasonic color pixels and pathologic vascularity measurements.

To determine which variable in the multiple linear regression contributed the most, the T-statistic was evaluated for each variable. The significant T-values are listed for the reduced and expanded data sets in Tables 3 and 4, respectively. For both the percent of area and percent of vessels in the five vessel ranges, the 30 to 39 μm vessel range contributed the most significantly to the linear relationship with the percent of color pixels post contrast injection, ($p = 0.001$ expanded and $p = 0.008$ as well as 0.002 reduced, respectively).

From the statistical analysis, it can be inferred that contrast enhanced color flow imaging provides some quantitative parameters, which correlate with direct pathologic vascularity assessments such as the iMVD. Specifically, the microvessel area and count for vessels 30 to 39 μm in diameter were most significant. This is in agreement with the qualitative observations of Burns et al. [11]. These results indicate that ultrasound imaging with contrast may produce a

quantitative measure of the neovascularity within breast tumors; similar to results recently obtained with MRI [12]. However, the current patient population is very small and until further patients are analyzed, these conclusions are preliminary.

The quantitative sub-study correlating contrast enhanced ultrasound and pathology has been presented at the AIUM and the Era of Hope, DoD Breast Cancer Research Meeting [13-14]. Results have also been published in a peer-reviewed journal [15] (see also Appendix II).

7. KEY RESEARCH ACCOMPLISHMENTS

- In total 43 patients studied using contrast enhanced 3D CAI.
- Marked increase in vascularity seen pre to post contrast imaging ($p < 0.01$).
- Contrast enhanced color flow imaging provides some quantitative parameters, which correlate with direct pathologic vascularity assessments.
- Contrast enhanced ultrasound images of breast tumor vascularity correspond to vessels 30 to 39 μm in diameter ($p = 0.006$ and 0.04).

8. REPORTABLE OUTCOMES

Manuscripts, abstracts, presentations

Chaudhari MH, Forsberg F, Voodarla A, Saikali FN, Goonewardene S, Needleman L, Shi WT, Finkel GC, Goldberg BB: Breast tumor vascularity identified by contrast enhanced ultrasound and pathology: initial results. *Ultrasonics*, 38, 105 – 109, 2000.

Forsberg F, Chaudhari MH, Voodarla A, Goonewardene S, Needleman L, Goldberg BB: Quantifying breast tumor neovascularity by contrast enhanced ultrasound and pathology: a comparative study. *J Ultrasound Med*, 19, S56 – S57, 2000.

Forsberg F, Chaudhari MH, Merritt CRB, Needleman L, Maitino AJ, Voodarla A, Goonewardene S, Goldberg BB. Contrast enhanced ultrasound imaging of breast tumors. *Proc Era of Hope, DoD Breast Cancer Research Meet*, 257 – 258, 2000.

April 2 - 5, 2000 The 44th Annual Convention of the American Institute of Ultrasound in Medicine, San Francisco, CA, USA.

- Quantifying breast tumor neovascularity by contrast enhanced ultrasound and pathology: a comparative study.

June 8 – 11, 2000. Era of Hope, Dept. of Defense Breast Cancer Research Meeting, Atlanta, GA, USA.

- Contrast Enhanced Ultrasound Imaging of Breast Tumors.
- Contrast Enhanced Ultrasound Imaging of Breast Tumors (poster).

9. CONCLUSIONS

In total, 21 patients with 6 cancers and 15 benign lesions have been enrolled in the Optison arm of the study. These numbers were much less than anticipated, due to personnel illness and changes. No data analysis has yet been carried out due to the limited data set available for Optison.

The histomorphometry system has been used to analyze vessel distribution and vessel density maps from 14 patients. Contrast enhanced color flow imaging was found to provide some quantitative parameters, which correlated with direct pathologic vascularity assessments such as the iMVD. Specifically, the microvessel area and count for vessels 30 to 39 μm in diameter were most significant. These results indicate that ultrasound imaging with contrast may produce a quantitative measure of the neovascularity within breast tumors. However, the current patient population in the sub-study is very small and further cases are currently being analyzed.

In summary, task 1 has been completed and tasks 2 and 3 are ongoing, but due to the unforeseen circumstances, only limited progress has been made this grant year. A one year no-cost extension with a carryover of the unspent balance was requested and granted to allow completion of the project, including data collection and analyses.

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11. TABLES

Table 1. Enrollment details for Optison patients.

Patient no.	age [years]	race	Diagnosis
1093	52	Caucasian	Non-proliferative fibrocystic changes
1094	50	Caucasian	Ductal hyperplasia
1095	54	Black	Fibrocystic changes
1096	61	Caucasian	In situ and invasive ductal carcinoma
1097	70	Caucasian	Fibroadenoma and fibrocystic changes
1098	65	Black	Infiltrating and intraductal carcinoma
1099	62	Caucasian	Sclerotic and focally calcified intraductal papiloma
1100	46	Caucasian	In situ and invasive ductal carcinoma

Table 2. Linear regression r^2 values with (significant p)

Data sets	Pathologic parameters	EXPANDED DATA Ultrasonic % Color Pixels		REDUCED DATA Ultrasonic % Color Pixels	
		Pre injection	Post injection	Pre injection	Post injection
All	Total MVA	0	0	0	0
masses					
$n_e = 60$	Total MVC	0	0	0	0
$n_r = 35$	MVA-5 ranges	0.02	0.25 (.006)	0.06	0.29 (.06)
	iMVD-5 ranges	0.02	0.13	0.04	0.31 (.04)
Benign	Total MVA	0	0	0	0
	Total MVC	0	0	0	0
$n_e = 35$	MVA-5 ranges	0.09	0.49 (.001)	0.18	0.73 (.001)
$n_r = 19$	iMVD-5 ranges	0.01	0.18	0.04	0.33
Malignant	Total MVA	0	0	0	0
	Total MVC	0	0	0	0
$n_e = 25$	MVA-5 ranges	0.35	0.32	0.71	0.60 (.05)
$n_r = 16$	iMVD-5 ranges	0.61	0.24	0.45	0.41

Table 3. T-statistic for significant variables: expanded data and % color pixels (p value)

Data set	Pathologic parameters	T – statistic value
All masses (post inj)	MVA by 30-39 μ m Vessels	4.07 (.001)
Benign (post inj)	MVA by 30-39 μ m Vessels	4.00 (.001)
	MVA by 40-49 μ m Vessels	1.97 (.06)

Table 4. T-statistic for significant variables: reduced data and % color pixels (p value)

Data Set	Pathologic Parameters	T – statistic Value
All masses (post inj)	MVA by 20-29 μ m Vessels	2.13 (.04)
	MVA by 30-39 μ m Vessels	2.85 (.008)
All masses (post inj)	iMVD in 30-39 μ m Range	3.41 (.002)
	iMVD in 50 & up μ m Range	2.62 (.01)
Benign (post inj)	MVA by 30-39 μ m Vessels	3.98 (.001)
	MVA by 40-49 μ m Vessels	1.88 (.08)
Malignant (post inj)	MVA by 40-49 μ m Vessels	3.91 (.002)

Appendix I

The Statement of Work from the original proposal:

Technical objectives 2 - 3

Task 1: Software development (months 1 - 6)

- a. Develop image analysis software for the histomorphometry system to allow vessel distribution (i.e., histogram) and vessel density maps to be produced from 3D image data.
- b. Develop 3D parameter extraction algorithms for the LIS 6000A system e.g., counting the number of interconnecting branches ("AV-shunts") and scoring the vessel tortuosity in collaboration with the consultant. Depending on the outcome of the statistical analysis, it is conceivable that new parameters will have to be extracted at a later date. Since the acquired 3D data volumes can be processed repeatedly this does not impact on the study design, it only demonstrates the flexibility of the data.

Technical objective 1

Task 2: Data collection (months 1 - 36)

- a. recruit 50 patients per year. This is about half of the anticipated number of patients being enrolled in the NIH supported contrast study.
- b. perform 3D CAI contrast studies as part of the already funded NIH project. This involves an extra injection of contrast (within the permitted total dose) and will add no more than 20 minutes to the total duration of the contrast study.
- c. research coordinator to collect clinical information (pathology results, etc.).

Technical objectives 2 - 3

Task 3: Data analysis (months 6 - 36)

- a. incorporate 3D imaging findings into the existing database (developed for the NIH supported contrast study).
- b. quantitate 3D CAI results in collaboration with the consultant.
- c. perform ROC analysis in collaboration with the statistician.
- d. perform remaining statistical analysis in collaboration with the statistician.

Appendix II

Reprint of article which appeared in *Ultrasonics*, 2000.

Breast tumor vascularity identified by contrast enhanced ultrasound and pathology: initial results

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Abstract

Quantifiable measures of vascularity obtained from contrast enhanced color flow images were correlated with pathologic vascularity measurements in ten female patients with a solid breast mass. Each patient received Levovist Injection® (Berlex Laboratories Inc., Montville, NJ). Color flow images pre- and post-contrast were obtained using an HDI 3000 unit (ATL, Bothell, WA) before removing the mass for pathologic vascularity assessments. Image-processing techniques were used to obtain both the ultrasound and pathologic vascularity measurements. Multiple linear regression found significant correlations for ultrasonic vascularity measurements post contrast and pathology ($P=0.02$ and 0.06). No correlations were found between pre-contrast ultrasound and pathology. In conclusion, post-contrast ultrasonic flow measures provide a non-invasive measure of breast tumor neovascularity. However, the patient population is small, and until further patients are analyzed, these conclusions are preliminary. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Color flow imaging; Image processing; Tumor neovascularity; Ultrasound contrast agents

1. Introduction

The goal of any breast imaging modality is to permit the early detection of tumors and to improve the differentiation between benign and malignant lesions, since these have been shown to significantly improve the chance of survival for patients with breast cancer [1]. Currently, the diagnosis of breast cancer is made with non-invasive techniques such as X-ray mammography, followed by invasive techniques such as excisional or aspirational biopsies. However, in 33% of patients, masses with no distinguishing features or with cystic/solid interiors cannot be diagnosed using mammography alone [2]. Moreover, the incidence of malignancy found by biopsy is very low, ranging from 10 to 35% [2]. To improve the early characterization of breast masses, thereby reducing the number of benign breast tumors biopsied, and to treat breast tumors in the most effective manner, the physiology of breast tumors must be understood.

Solid tumor growth and metastasis are dependent on

angiogenesis, a process where blood vessels sprout from preexisting microvessels [3,4]. Tumor angiogenesis or neovascularity has been suggested to provide prognostic information on tumor malignancy [4]. It can be assessed invasively by intratumoral MicroVessel Density (iMVD), which is an independent pathologic predictor of tumor angiogenesis and tumor state [4–7]. Ultrasound imaging is currently an auxiliary modality in breast imaging. Evaluation of the morphology of breast tumor vascularity with contrast-enhanced Doppler ultrasound could provide a non-invasive diagnostic criterion similar to iMVD. To date, breast cancer diagnosis based on standard Doppler ultrasound flow detection has produced mixed results [8–10]. This may be due to the lack of sensitivity of Doppler techniques in detecting the small vessels and slow flow associated with tumor neovascularity. To improve the sensitivity and specificity of breast ultrasound, intravenously administered microbubble based contrast agents, which produce up to 25 dB increase in blood flow signal intensities, have been used [11].

This study was conducted to determine whether quantifiable measures of lesion vascularity obtained from Doppler flow images pre- and post-contrast administra-

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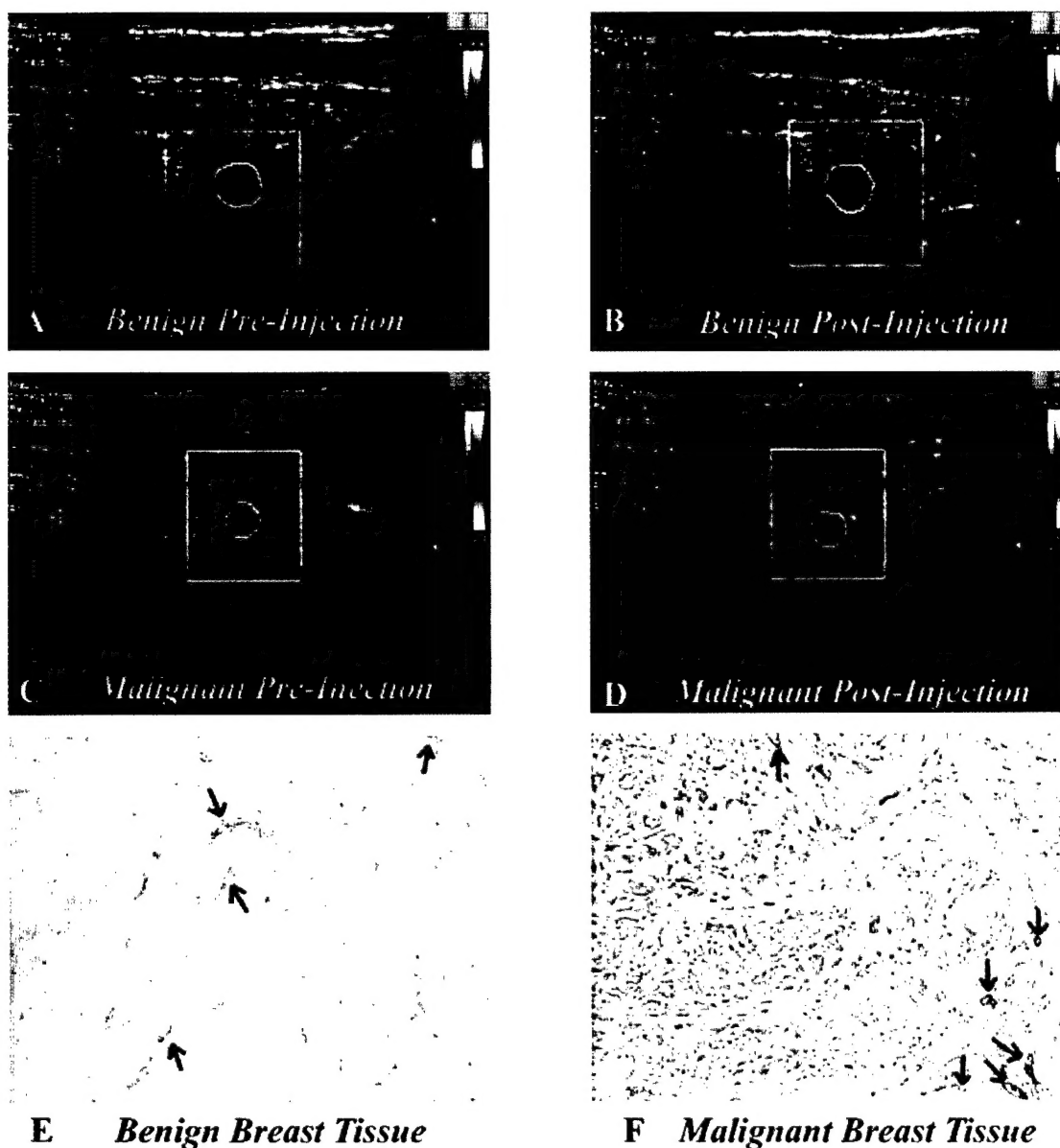


Fig. 1. Color Doppler ultrasound of a benign breast mass (outlined in yellow) before (A) and after (B) contrast injection, likewise for a malignant tumor pre- (C) and post- (D) contrast. Microscopic view (100 \times) of the benign (E) and malignant (F) mass, showing microvessels stained with CD31 (arrows).

tion correlated with pathological assessments of vascularity as a first step towards non-invasive ultrasonic characterization of breast tumors.

2. Materials and methods

Ten female patients with a solid breast mass diagnosed by X-ray mammography and who were scheduled for an excisional biopsy received an intravenous bolus of Levovist Injection® (Berlex Laboratories, Montville, NJ) at a dose volume of 10 ml, concentration of 300 mg/ml. Color flow images of the masses were obtained pre- and post-contrast using an HDI 3000 unit

(ATL, Bothell, WA). Transaxial scans of the mass were performed at five levels, each encompassing 20% of the cranio-caudal dimension. The color flow images at the point of maximal enhancement were recorded for each level. The Institutional Review Board of the university approved the study, and all patients signed informed consent.

Specimens were sectioned in the same plane as the ultrasound images and stained with an endothelial cell marker, CD31, and mounted onto glass slides. The vascular morphology of the tissue, specifically, the number and area occupied by tumor vessels, was determined by a semi-automated histomorphometry system based on an SMZ-10A microscope (Nikon, Melville,

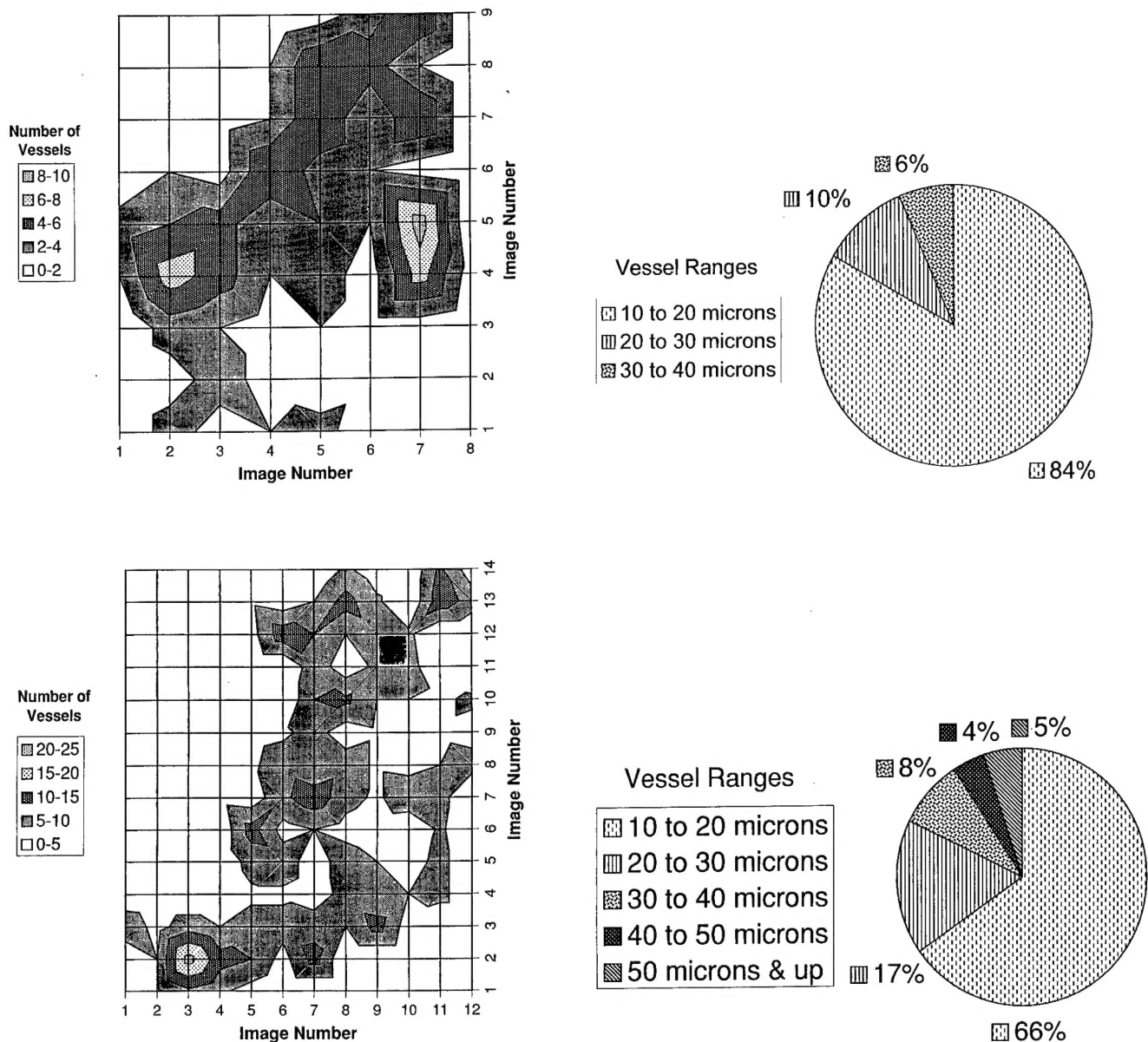


Fig. 2. Vascularity map with the number of vessels per image and their distribution within the five ranges for the benign (A and B) and malignant (C and D) mass, respectively.

NJ) and ImagePro Plus software (Media Cybernetics, Silver Spring, MD). Using a Sony CCD camera, the entire specimen area was digitized under $100\times$ magnification. For this study, 31 slides, with a total of 5756 frames (dimensions: 640 pixels by 480 pixels or 1.27 mm^2), were examined. The number of color pixels on the color flow images relative to the pixel size of the mass can be used as a first-order measure of mass vascularity [12]. Frozen ultrasound images were digitized before and after contrast injection. A total of 100 digitized scans were examined in this study.

Both the slide and video image analyses were patterned after chromaticity analysis methods used by Barbareschi et al. and Bell et al., respectively [13,14].

For each captured RGB color image of tumor area, the slide image processing consisted of extracting vessel (saturation image) and tissue (blue image) enhanced images and performing mathematical morphometry to obtain an image on which automated counts and measurements of microvessels were performed. For each slide, the total microvessel area (MVA) and count (MVC) were determined and divided into five categories: vessel diameters between (1) 10 and $19\text{ }\mu\text{m}$, (2) 20 and $29\text{ }\mu\text{m}$, (3) 30 and $39\text{ }\mu\text{m}$, (4) 40 and $49\text{ }\mu\text{m}$, and (5) $50\text{ }\mu\text{m}$ and above. The ultrasonic image processing consisted of extracting red, green, and blue images and performing mathematical morphometry to obtain an image only with color pixels. From the video analysis, the percen-

tage of color pixels within the mass was calculated for each level before and after contrast administration.

To determine whether a linear relationship existed between pathologic and ultrasonic vascularity measurements, an equal number of data points must be assessed from both methods. Ten ultrasonic data points per patient (five pre- and five post-contrast, 100 in total) were consistently obtained because a hand-held transducer was used, and, regardless of the size of the mass, scans at five levels of each mass could always be taken (albeit sometimes with some overlap between the levels). However, due to the size of some masses, five pathologic sections of a mass were sometimes not possible resulting in a total of 31 pathologic data points. To be able to compare the data sets, two solutions were developed, which ensured an equal number of points in both data sets. One solution required ultrasonic data to be averaged and replaced until, for each patient, the number of scans equaled the number of pathology slides (i.e. data reduction). The other solution required pathologic data to be averaged and added to the number of slides for each patient until five data points were reached (i.e. data expansion). A statistical analysis was performed to determine whether ultrasonic flow data (pre- or post-contrast) correlated with pathologic data in breast tumors. The linear relationship between ultrasonic and

pathologic data was assessed using single- and multiple-variable linear regression techniques.

3. Results

Fig. 1 shows sample digitized ultrasonic and pathologic images for both a benign and a malignant breast mass, while Fig. 2 shows the corresponding vascularity maps depicting the number of vessels and a distribution of vessels by the five vessel ranges for both samples. There was a significant increase in the number of ultrasound color pixels pre- to post-contrast injection ($P < 0.003$). No statistical difference in ultrasonic color pixels was found between the benign and malignant masses. Table 1 gives the r^2 values for the linear regression for the reduced and expanded data sets. The multiple linear regression technique for the entire data set (i.e. benign and malignant lesions evaluated jointly) revealed significant correlations for ultrasonic color pixels post-injection with the percentage of area in the five vessel ranges (expanded MVA; $P = 0.02$) and with the percentage of vessels in the five vessel ranges (reduced iMVD; $P = 0.06$). No correlations were found between pre-contrast ultrasonic color pixels and pathologic vascularity measurements using the entire data set.

Table 1
Linear regression r^2 values with (significant P)

Data sets	Pathologic parameters	Expanded data		Reduced data	
		Ultrasonic percentage color pixels		Ultrasonic percentage color pixels	
		Pre-injection	Post-injection	Pre-injection	Post-injection
All masses	Total MVA	0	0	0	0
$n_c = 50$	Total MVC	0	0	0	0
$n_r = 19$	MVA-5 ranges	0.15	0.25 (0.02)	0.18	0.30 (0.09)
	iMVD-5 ranges	0.09	0.14	0.03	0.32 (0.06)
Benign	Total MVA	0	0	0	0
	Total MVC	0	0	0	0
$n_c = 30$	MVA-5 ranges	0.34 (0.06)	0.49 (0.003)	0.43	0.73 (0.004)
$n_r = 10$	iMVD-5 ranges	0.13	0.19	0.05	0.36
Malignant	Total MVA	0	0	0	0
	Total MVC	0	0	0	0
$n_c = 20$	MVA-5 ranges	0.33	0.33	0.71 (0.03)	0.59
$n_r = 9$	iMVD-5 ranges	0.62 (0.009)	0.34	0.43	0.40

Table 2
 T -statistic for significant variables: expanded data and percentage color pixels (P value)

Data set	Pathologic parameters	T -statistic value
All masses (post-injection)	MVA by 30–39 μm vessels	3.00 (0.004)
Benign (post-injection)	MVA by 30–39 μm vessels	3.65 (0.001)
	MVA by 40–49 μm vessels	1.83 (0.08)
Benign (pre-injection)	MVA by 40–49 μm vessels	2.18 (0.04)
	MVA by $\geq 50 \mu\text{m}$ vessels	3.66 (0.001)
Malignant (pre-injection)	iMVD in 40–49 μm range	3.95 (0.001)

Table 3

T-statistic for significant variables: reduced data and percentage color pixels (*P* value)

Data set	Pathologic parameters	T-statistic value
All masses (post-injection)	MVA by 10–19 μm vessels	1.90 (0.07)
	MVA by 20–29 μm vessels	2.05 (0.05)
	MVA by 30–39 μm vessels	2.00 (0.06)
	iMVD in 30–39 μm range	3.05 (0.005)
	iMVD in ≥ 50 μm range	2.60 (0.02)
Benign (post-injection)	MVA by 30–39 μm vessels	3.72 (0.003)
	MVA by 40–49 μm vessels	1.76 (0.01)
Malignant (pre-injection)	MVA by 40–49 μm vessels	4.01 (0.003)

To determine which variable in the multiple linear regression contributed the most, the *T*-statistic was evaluated for each variable. The significant *T*-values are listed for the reduced and expanded data sets in Tables 2 and 3, respectively. For both the percentage of area and percentage of vessels in the five vessel ranges, the 30–39 μm vessel range contributed most significantly to the linear relationship with the percentage of color pixels post-contrast injection ($P=0.004$ expanded and $P=0.005$ reduced, respectively). Note, that the pre-injection ultrasound vascularity measures from benign masses have the most significant contributions from larger vessels (≥ 40 μm) than the post-injection measures (Table 2).

4. Conclusions

From the statistical analysis, it can be inferred that contrast-enhanced color flow imaging provides some quantitative parameters, which correlate with direct pathologic vascularity assessments such as the iMVD. Specifically, the microvessel area and count for vessels 30–39 μm in diameter were most significant. This is in agreement with the qualitative observations of Burns et al. [15]. These results indicate that ultrasound imaging with contrast may produce a quantitative measure of the neovascularity within breast tumors; similar to results recently obtained with MRI [16]. However, the current patient population is very small, and until further patients are analyzed, these conclusions are preliminary.

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